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On the adaptation of an intermediate-image β-spectrometer to pair spectroscopy

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With 10 figures in the text

Introduction

When one is faced with the problem of measuring γ-ray energies greater than ≈ 3 MeV with good resolution one has to choose between scintillation spectrometers and magnetic spectrometers. NaI scintillation detectors have high efficiency but rather poor resolution, about 5 % at the most favourable energies. In a 3-crystal pair spectrometer [1] the resolution is ≈ 3 % between 1 and 3 MeV and for higher energies not much better than a single detector. When a magnetic spectrometer, which has higher inherent resolution, is utilized for γ-ray energy measurements of $\geqslant 3$ MeV the pair production process is favourable since the probability for pair production increases, whereas the Compton and photoelectric cross sections decrease, with increasing γ-ray energy.

Magnetic pair spectrometers of two general designs have been proposed, namely the uniform field spectrometer by McDaniel, von Dardel and Walker [2] and the axially-focussing pair spectrometer. The first spectrometer of the latter type was constructed by Siegbahn and Johansson [3]. They used a magnetic lens with the source placed slightly off the axis, giving different focal-points for the electron and the positron, and a pair was detected as a coincidence between the two detectors. The statistical-separation lens-type pair spectrometer was then proposed by Bame and Baggett [4] and by Alburger [5]. In their constructions the source is placed on the magnetic axis and the axially slightly off-focus detecting area is divided into two parts. A coincidence is recorded when the electron and positron enter the different halves of the detector. The spectrometer current must thus be adjusted to focus electrons of the energy $\frac{1}{2}(E_\gamma - 1.02)$ MeV to obtain the peak of the coincidence line whose half-width depends on the spectrometer resolution. A pair spectrometer based on an entirely different principle has recently been suggested by Malmfors [6]. In this construction the flight-times of the electrons and positrons are measured. The trajectories of the electrons and positrons are "stretched out" by having them go in trochoidal orbits in different directions in an inhomogeneous magnetic field. Their flight-times are then essentially inversely proportional to their energy. A spectrometer based on this principle is under construction at the Nobel Institute. The advantages with the two last-mentioned instruments over the uniform field spectrometer are the higher transmission and the fact that an uncollimated source of γ-rays can be used, allowing for instance the study of nuclear or internal pairs produced in an accelerator target.

Of the magnetic lens-type spectrometers available the intermediate-image spectrometer developed by Slätis and Siegbahn [7] is the most suitable for the statistical-separation principle because of its high transmission. The two intermediate-image statistical-separation pair spectrometers by now reported are both of the iron-free type [8], namely the spectrometer at the Rice Institute by Bent, Bonner and Sippel [9] and that at Brookhaven by Alburger [10]. In this paper the construction of a pair spectrometer, based on a factory-built Slätis–Siegbahn iron-jacketed spectrometer [11] is described.

General data of the LKB-spectrometer

This spectrometer has for some time been used as an ordinary β-spectrometer and measurements of its resolution and transmission have been performed by Slätis [12]. Table 1 is reprinted from this paper. From this table it is seen that the line width contribution due to source size is about 0.7 % per mm of diameter. The magnet has been constructed to allow the focussing of electrons of up to 7 MeV energy, thus making it possible to measure γ-ray energies of up to 15 MeV with the pair technique. At this energy the magnet current amounts to 600 amp. Provided ample cooling is used, the magnet can be overloaded during about 15 minutes at a time up to 700 amp corresponding to 8.3 MeV β-energy, i.e. 17.6 MeV γ-ray energy. The current is measured with a high precision millivoltmeter which gives the voltage across a resistor connected in series with the magnet. Fig. 1 shows a schematic cross-section of the spectrometer. The first baffle R_1 consists of two parts which permits the distances a and b to be continuously varied from the outside of the spectrometer. The purpose of this baffle is to remove the large low energy tail on a conversion line, which would result without the baffle, by cutting out those rays which leave the source at too large or too small angles. Fig. 2 shows a photograph of the electron trajectories which was used as a basis for the construction of the first baffle. The intermediate-image baffle R_2 has a fixed outer edge while the inner edge, formed as a photographic diaphragm is continuously variable from the outside of the spectrometer. The slit width can be varied from 0 to 10 mm. The annulus is made slightly elliptical to compensate for an asymmetry in the magnetic field (the maximum deviation of the annulus from a circle is only 0.5 mm).

Table 1. Resolution and transmission in some cases for the LKB beta-spectrometer.

Sample diameter mm	Slit width of intermediate image baffle mm	Resolution U %	Transmission T %
1	1	1.0	1.9
1	2	1.1	4.0
1	5	2.2	7
2	2	1.8	3.3
2	5	2.5	7

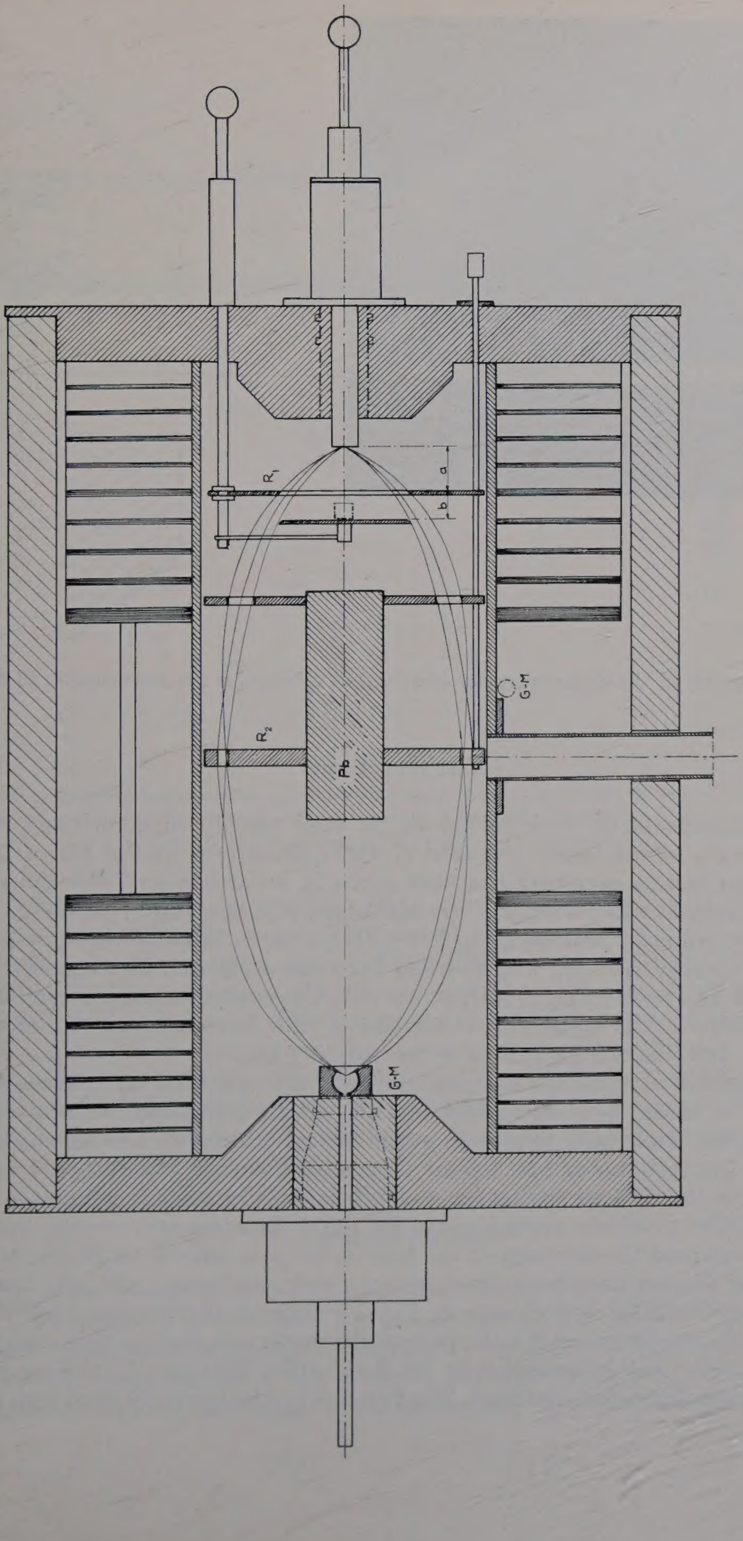

Fig. 1. Schematic cross-section of the LKB-spectrometer. The dashed lines represent the changes for the pair spectrometer adaptation.

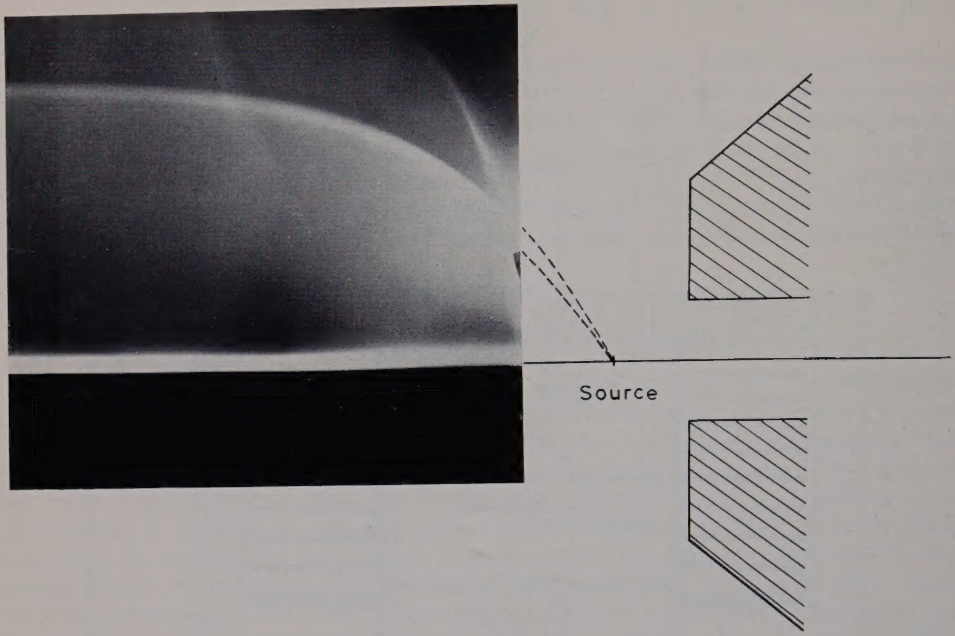

Fig. 2. Photograph of the electron trajectories used as a basis for the construction of baffle R_2.

The target-side

The pair-spectrometer is intended to be used mainly in connection with the extracted beam of the small cyclotron (7 MeV, deuterons) at the Nobel Institute. A description of this cyclotron has been given in an article on "The time-of-flight technique applied to fast neutrons" by Malmfors, Kjellman and Nilsson [13] so that only a short summary will be given here. The beam is brought through a vacuum tube into an adjacent room, well shielded from the cyclotron. The beam is focussed by means of two sector magnets in series with the cyclotron magnet and a pair of quadrupole lenses. The image area is less than 1 cm^2. Beam currents are of the order of 5–10 μA and the energy spread is less than ± 1 %.

The connection between the vacuum-tube from the cyclotron and the spectrometer (see Fig. 3) is made as a unit which includes a vacuum-valve, two tantalum collimators and the electrically insulated target mount which can be cooled with water or oil. The first collimator has a 6-mm diameter hole and the second 1 or 2 mm, depending on the desired resolution and intensity. The second collimator is water-cooled. In order to obtain enough space for the collimators and cooling lines it was necessary to extend the diameter of the hole in the pole-piece from 26 mm to 40 mm. The effect of this on the best axial source position was tested, and was found to be barely noticeable. The dotted lines in Fig. 1 represent the changes that had to be made with the spectrometer for the pair spectrometer adaptation. As is seen from this figure, a Faraday cup is connected to the first baffle. This permits the beam current to be read when thin targets are used. The Faraday cup is internally lined with tantalum

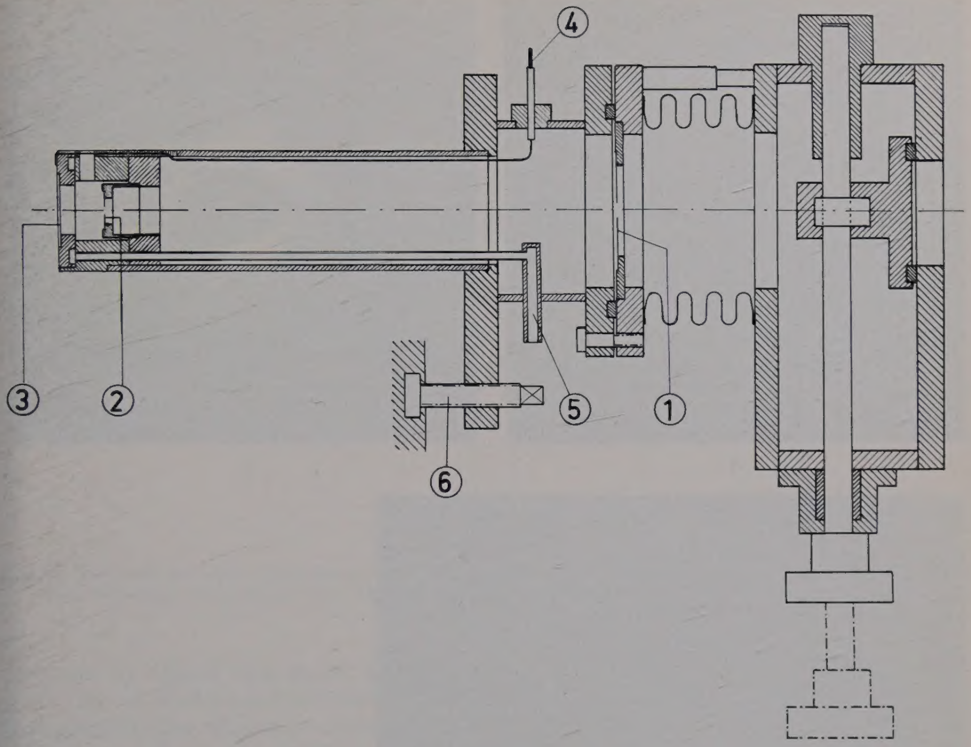

Fig. 3. The connection between the vacuum-tube from the cylotron and the spectrometer. *1*, First collimator; *2*, second collimator; *3*, target holder; *4*, current measuring connection; *5*, cooling line; *6*, screw arrangement for axial adjustment.

to reduce the background. When thick targets are used the current measuring device is connected directly to the target. The current can be read on a μA-meter or on a current integrator of the type described by Mileikowsky and Pauli [14]. A small GM-monitor is also inserted in the spectrometer near the target at a place well shielded from the collimators. This is perhaps the best indicator of the number of events in the target, at least for relative measurements. For instance a variation in yield, resulting from disintegration of the target is detected by the GM-monitor but not by the current measuring device. The monitor can be made to cut off the coincidence counter when a certain number, large enough not to introduce any significant error, of monitorpulses is recorded.

The detector side

A GM-counter is used as a detector in the ordinary β-spectrometer with a small hole ($\varnothing = 12$ mm) in the pole-piece for the gas filling. For the pair detection a wide conical hole to accomodate the light guides had to be made (see Fig. 1). This of course caused a rather large change in the magnetic field distribution near the focus. The result of this change was investigated experimentally by a photographic technique.

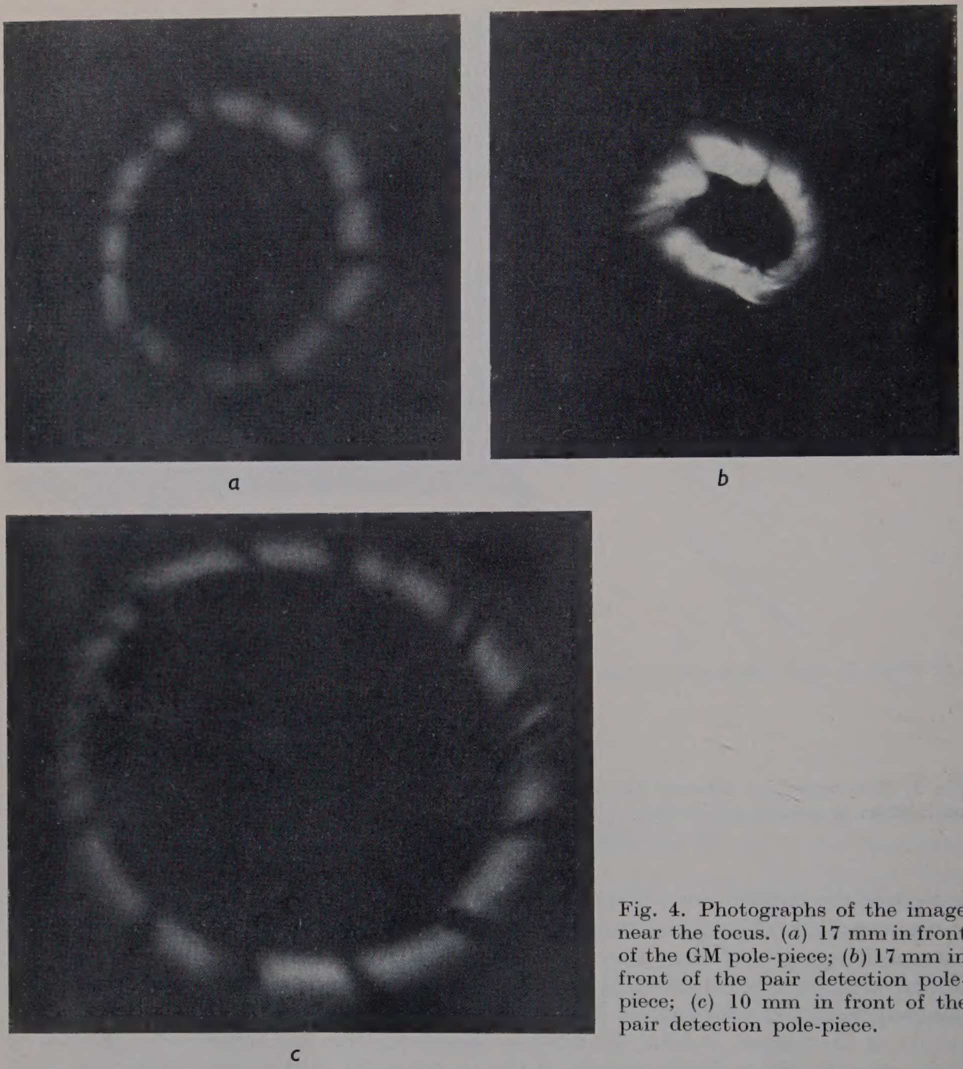

Fig. 4. Photographs of the image near the focus. (*a*) 17 mm in front of the GM pole-piece; (*b*) 17 mm in front of the pair detection pole-piece; (*c*) 10 mm in front of the pair detection pole-piece.

Photographic plates were inserted at various distances from the two different pole-pieces and exposed to the electrons from the *F*-line of Th B. Fig. 4 shows some of the results. It is seen that the focus which is situated 25 mm from the GM pole-piece has moved to 20 mm from the pair detection pole-piece. At the same time the angle between the axis and the electrons at the focus has changed from approx. 50° to approx. 63°.

These plates were also used as a basis for determining the best crystal size and their optimum distance from the pole-piece. As is seen from Fig. 5 this distance appears to be somewhere between 18 and 14 mm (measured to the front of the crystals). This was later confirmed by actual measurements with the pair detector. The whole detector system including amplifiers and the coincidence circuit is axially

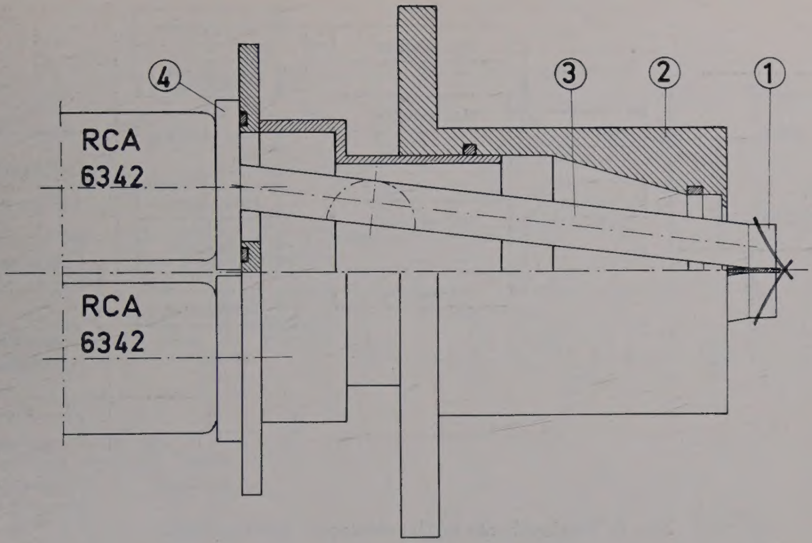

Fig. 5. The pair detection pole-piece with the light-guide arrangement. *1*, The plastic scintillators (the electron trajectories are sketched); *2*, pole-piece; *3*, light-guide; *4*, plastic bolt.

movable by means of a screw arrangement and a sliding O-ring seal a distance of ≈ 25 mm to make readjustments possible after, for instance, a change to another crystal thickness. The crystals used for the calibration of the apparatus were plastic scintillators (Plastifluor "B" from the Pilot Chemical Co.) with a diameter of 30 mm (semicircular cross-section) and a thickness of 10 mm. This thickness is sufficient to stop electrons of up to ≈ 4 MeV. The crystals are separated by a 2 mm thick tungsten absorber. The semicylindrical plastic light-guides have a length of 170 mm and the same diameter as the crystals. They are glued to 8 mm thick plastic bolts, 60 mm in diameter, which make a vacuum-tight connection to the spectrometer with the help of O-rings (see Fig. 5). The crystals and light-guides are aluminized to decrease light losses. On the basis of earlier experiences with another iron-clad Slätis–Siegbahn spectrometer it was felt that the chosen length of the light-guides was sufficient for the photomultipliers not to be affected by the stray magnetic field from the spectrometer. However, presumably due to the off-axial position of the photomultipliers, a slight decrease in pulse height with increasing magnet current was noticed. μ-Metal shields were arranged around the photomultipliers to correct for this.

The electronic equipment

Fig. 6 shows a block-scheme of the electronic arrangement. The detector pulses are sent partly via a fast amplifier containing a delay-line of 1 μs to a gated fast pulse generator and partly to a discriminator circuit which delivers gate-pulses to the pulse generator. As the pulse generator has a certain triggering level it will be triggered earlier by a large pulse than by a small one. To compensate for this a trigger-time correcting circuit is included. The pulse generator produces pulses of

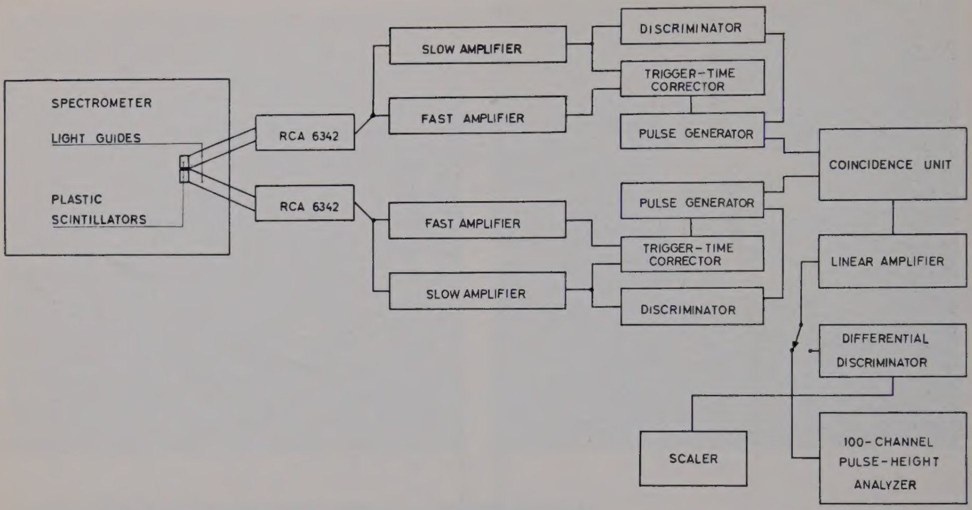

Fig. 6. Block-scheme of the electronic arrangement.

short duration for the coincidence circuit. The pulse generator, the trigger-time corrector and the coincidence unit have been described in detail by B. Johansson elsewhere [15].

As mentioned above the electrons are detected with plastic scintillators, and in order to preserve the rise-time (about 3 mμs) obtained with these scintillators a fast amplifier was designed. A complete wiring diagram is given in Fig. 7. When no certain delay is required, distributed amplifiers are to be preferred for fast pulse amplification. In this case, however, when a delay of 1 μs is desired a distributed amplifier is intricate to construct because it is difficult to adjust the delays in the anode and grid lines to be equal. If this adjustment is not exact, phase distortion will easily appear. Our amplifier is built up of 5 stages with a delay of 0.2 μs in each stage. The delay-lines act as coupling elements. The stray capacitances in the anode and grid circuits are elements of the delay-lines and are thus compensated for. The amplifier gives a max. amplification of 125 at a rise-time of 50 mμs. (The pulse generator used in this test had an optimum rise-time of 30 mμs.) Fig. 7 also shows a wiring diagram of the slow amplifier (rise-time: 0.2 μs) which delivers pulses to the discriminator circuit. Since the discriminator operates on the top of the input pulses, the firing point is not certain. This will give a delay which varies within the rise-time of the pulses. This is the reason for supplying the fast amplifier with a delay of 1 *μs*.

The coincidence unit (see Fig. 8) contains a 6BN6 tube, the anode circuit of which delivers output pulses with amplitudes proportional to the overlapping of the input pulses. The circuit thus operates as a time-to-pulse-height converter. This feature is described elsewhere [16, 17] and is planned for use in measuring short half-lives of excited states (see the last section). In pair-detection the output pulses from the coincidence unit are fed to a differential discriminator, the channel width of which determines the resolving time. The optimum resolving time in our case is about 1 mμs. In order to obtain the real and chance coincidences at the same time, which is an advantage when the ratio between them is low, the output pulses from the coincidence unit can also be fed to a 100-channel pulse-height analyzer.

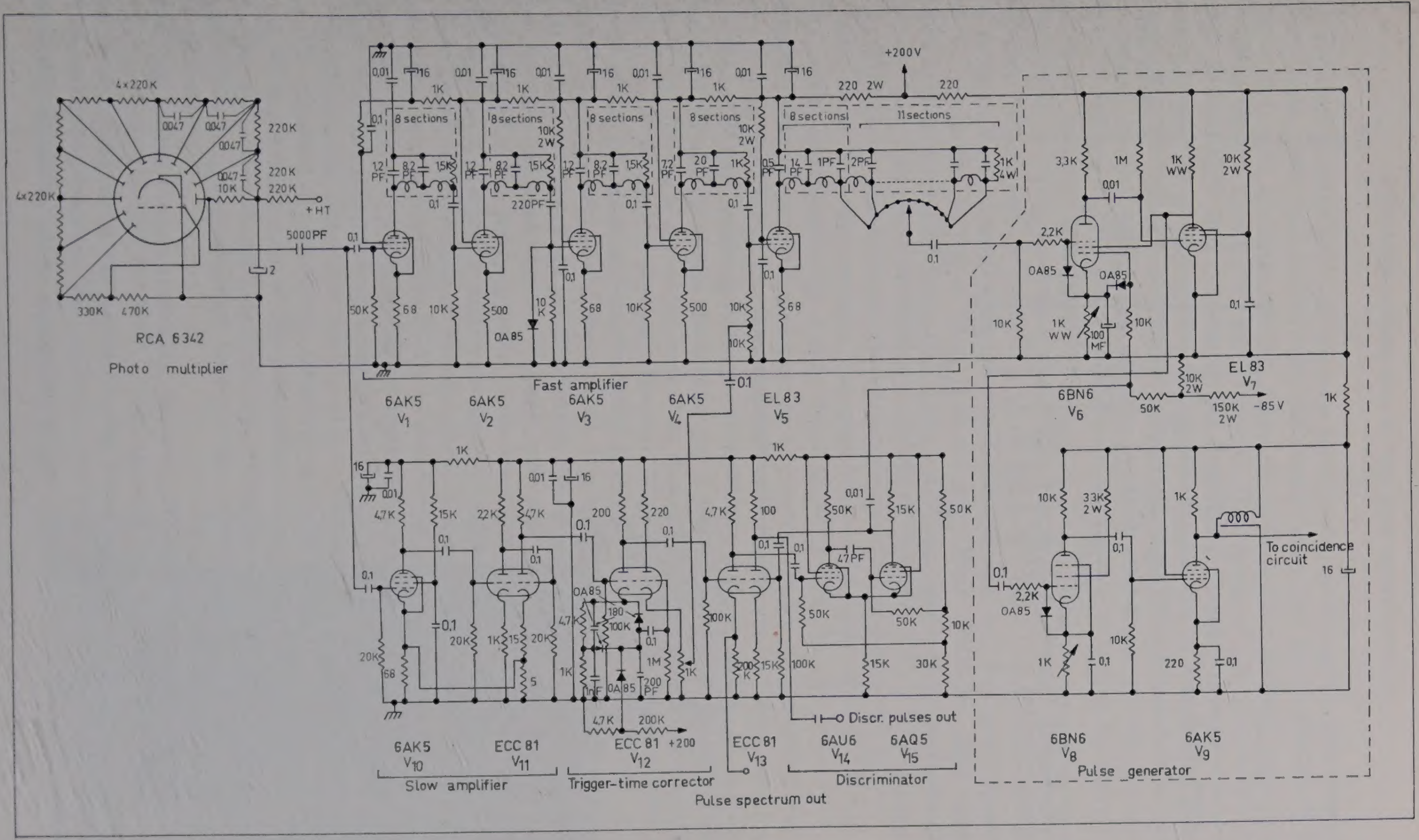

Fig. 7. Wiring diagram of one of the channels.

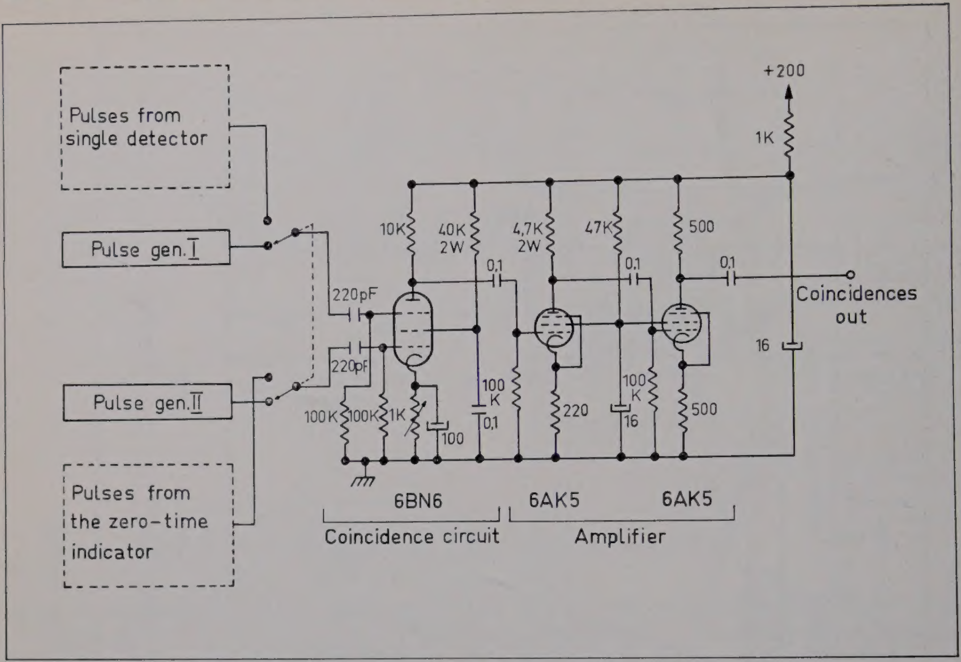

Fig. 8. The coincidence unit.

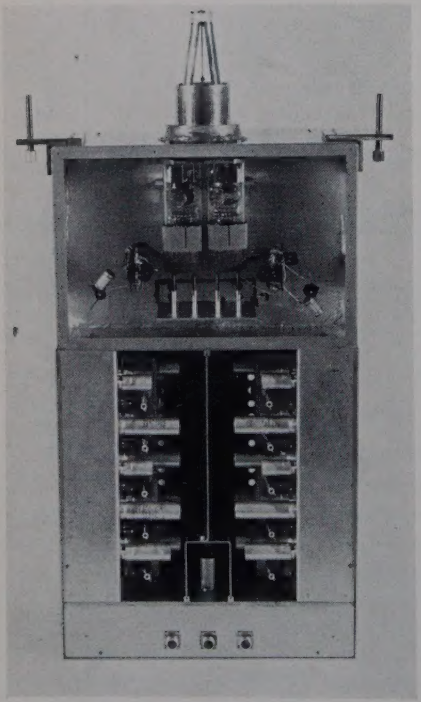

Fig. 9. Photograph of the electronic arrangement.

Test and calibration of the pair spectrometer

For the testing of the pair spectrometer the cyclotron-induced reaction $F^{19}(p,\alpha)O^{16*}$ has been used. As is well known both the ground state and the first excited state in O^{16} have zero spin and even parity; γ-ray emission is thus strongly forbidden and the nucleus decays directly by pair emission. The energy of this pair emitting state is 6.065 ± 0.009 MeV [10]. The state has a relatively long life-time (5×10^{-11} sec) so that it is reasonable to expect that the nucleus forgets how it was formed before the pair emission. The emission of individual pair electrons should therefore be isotropic with respect to the beam. The positron-electron correlation in this transition is $W(\theta) = 1 + 0.6 \cos \theta$ [18]. The coincidence counting-rate will thus be slightly larger than for an isotropic correlation.

The targets we have used have been CaF_2 evaporated onto a 1 μ thick Ni-foil to a thickness of ≈ 3 mg/cm^2 and 10 μ thick foils of $(CF_2)_n$. Coincidence curves have been measured at several different resolution settings of the spectrometer. The observed resolution is better than that for conversion electrons. This effect that has also been observed by Bent *et al.* [9] and Alburger [10] is easily understood if one considers that if an electron of energy dE higher than the $\frac{1}{2}(E_\gamma - 1.02)$ mean energy passes through the spectrometer then the corresponding positron will have an energy dE lower than the mean energy. The pair line should thus have the shape of the square of the distribution for a conversion electron line, i.e., its half-width should be a factor $1/\sqrt{2}$ better. For instance, at 2 % resolution for conversion electrons the observed pair resolution for the same source size amounts to 1.3 %. A coincidence curve of the O^{16} pair emitting state of this resolution is shown in Fig. 10. A calculation of the total number of target transitions per a certain number of monitor pulses can be made by making a run of the complete electron spectrum from the reaction with a GM counter instead of the pair detector. This electron spectrum consists almost entirely of the electrons and positrons from the pair emitting state. Such an experiment has been performed and shows that at a pair resolution of 1 % the coincidence counting rate is 0.5 counts per 10^5 target transitions.

For the measurement of γ-ray energies with this pair-detection technique internal pairs produced in the product nuclei of the reactions can be observed. The probability of this process is low and if higher intensity is necessary an external converter must be used. This gives of course an energy spread depending on the converter thickness. It generally can be said that if one is satisfied with a resolution of $\geqslant 5$ % the use of an external converter gives higher intensity, and that when higher resolution is wanted, internal pairs will give more intensity.

The background effects are mainly of four different kinds.

1. The accidental coincidence counting rate. This can be kept very low thanks to the short resolving time of the coincidence circuit.

2. The coincidences resulting from high energy electrons producing pulses in both crystals. The tungsten absorber between the crystals and the discriminator bias reduce this effect.

3. Coincidences due to annihilation photons. If the discriminator bias is high enough to exclude pulses due to 0.5 MeV γ-rays, the only possibility left for this process to produce coincidences is the simultaneous absorption of the annihilation quantum and an unrelated electron. This will also be a small effect due to the short resolving time of the detector.

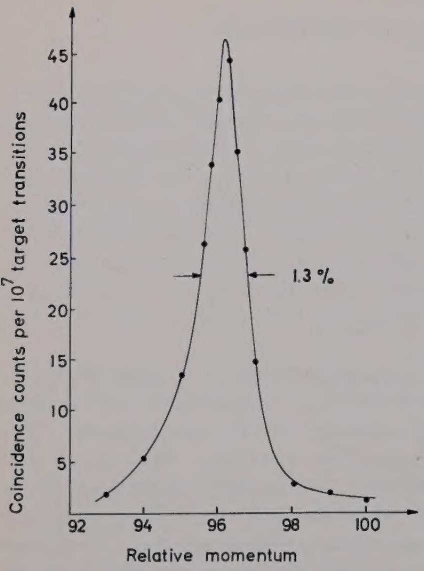

Fig. 10. Coincidence curve of the 6.065 MeV transition in O^{16}.

4. Scattering of high-energy γ-rays or neutrons from the walls of the spectrometer. This effect is reduced by having the cyclotron beam well collimated and also by the biasing of the detectors.

In any of these cases the chance coincidence counting rate can be observed simultaneously with the real counting rate with help of the 100-channel analyzer, as mentioned before.

Further applications of the spectrometer

It is a simple matter to convert the pair spectrometer back to an ordinary β-spectrometer as the source-holder has been extended to fit in the larger hole in the pole-piece and as the GM pole-piece is left intact.

Besides this a new application of the spectrometer is planned. As mentioned above the coincidence unit operates as a time-to-pulse-height converter. This makes it usable for measuring short half-lives of excited states. For this purpose the pair detector can be replaced by a single detector consisting of a thin scintillator coupled to a photomultiplier via a short light-guide. This detector registers the conversion electrons from an excited state. The photomultiplier is inserted in the pole-piece so that its flat cathode is almost in line with the innermost side of the pole-piece. An O-ring seal makes a vacuum-tight connection around the circumference of the photomultiplier (see Fig. 5). In order to have no influence on the pulse-height of the magnetic field inside the pole-piece a compensating coil is wound around the photomultiplier [15]. For determining the time when a state is born use is made of the natural phase-bunching of the cyclotron. A photomultiplier with a fast scintillator looks at part of the cyclotron beam near the target and the pulses from this indicator are fed to one side of the coincidence circuit. The pulse width is ≈ 3 mμs and the distance between two pulses is 82 mμs. (For further details on this system of zero-time indication see [13, 19].) By feeding the pulses from the electron detector to the other side of the coincidence circuit a delayed or prompt coincidence curve is obtained. The dashed squares in Fig. 8 indicate what changes have to be made for this application. The lower limit of the half-life of an excited state measurable by this technique can be expected to be a fraction of a millimicrosecond.

SUMMARY

An iron-jacketed intermediate-image β-spectrometer has been adapted for high energy γ-ray measurement from cyclotron-induced reactions. The technique that has been used is the so-called statistical-separation pair detection technique.

The apparatus has been tested and calibrated with help of the 6.065 ± 0.009 MeV pair emitting state in O^{16}.

Finally a method of using the spectrometer for measuring short half-lives of excited states is described. The natural phase-bunching of the cyclotron is then used as an indicator of the time when a state is born.

ACKNOWLEDGEMENTS

Our sincere thanks are due to Professor Hilding Slätis for suggesting the measuring of the energy of gamma-rays emitted from light elements during the bombardment with protons or deuterons from the cyclotron. The LKB beta-spectrometer should be used for this energy measurement. We are also much indebted to him for his interest and encouragement during the course of this work. We also wish to express our appreciation to Mr. T. Appelquist for help with the cyclotron runs.

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